Metallo-dielectric Structure with Negative Refractive Index for Millimeter Applications

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***Abstract*-We have designed and experimentally demonstrated a left-handed metamaterial working at microwave frequencies. An inexpensive mechanical-machining technique was used to fabricate a so-called fishnet metamaterial out of metal-dielectric-metal structure. Our proposed metamaterial exhibits a negative refractive index with the W-band of around 85 GHz in both simulation and experiment. The originality brought by our investigated structure is its simplicity in manufacturing and its functioning with a double polarization (TE and TM modes). These make it suitable in many hopeful millimeter applications such as super-resolution-imaging, magnetic resonance imaging, bio-sensing and so on. Furthermore, the use of a flexible and thin dielectric substrate makes our structure very promising for conformal geometric applications (e.g., radar absorbers aboard military aircrafts).**

Keywords-Component; Metamaterials; Negative refractive index; Super-resolution

I. INTRODUCTION

In recent years, a new kind of materials commonly called *metamaterials* has revolutionized the world of physics with unusual properties that do not exist in nature. Indeed, metamaterials offer possibilities to manipulate electromagnetic waves in an extraordinary way. Since the pioneering work of Victor Veselago on the general properties of wave propagation within negative refractive index media in 1968, a large number of researchers have contributed to the development and the growth of this new generation of materials. In this paper, we propose to investigate a well-established fishnet metamaterial (metal-dielectric-metal), which is designed to exhibit a negative refractive index at microwave regime.

Fishnet metamaterials were initially introduced as structures with negative refractive index and low losses at near-infrared frequencies [2]. They subsequently demonstrated in microwave and terahertz frequencies [3-4], and are in the far-infrared frequency range [5-6] and in the visible range [7]. The fishnet structure also aims to be an alternative to the conventional structure consisting of a combination of SRR (Split Ring Resonators) and continuous wires, initially proposed by J. B. Pendry *et al* [8-9], fabricated and then characterized by R. A. Shelby *et al* at microwave frequencies [10].

Although the SRRs ⁄ continuous-wires based metamaterial exhibits a negative refractive index, the multilayer topology of the structure, which is illuminated at grazing incidence, remains a major disadvantage of this class of metamaterials. So it is very difficult or even virtually impossible to fabricate unit cells of complex geometry with submicron or nanoscale sizes. Further drawbacks related to physical phenomena also limit the functioning of this structure at very high frequencies. The advantage of the fishnet metamaterial is its simplicity of manufacture. Furthermore, only one single layer excited at normal incidence is sufficient to exhibit a negative refractive index at the desired frequency. In the following sections, we will study a perforated metal-dielectric-metal structure that exhibit a negative refractive index around 85 GHz.

II. HOLES-ARRAY METAMATERIAL: DESIGN SPECIFICATIONS

Our investigated metamaterial is shown in Fig. 1(a) fig1a. It consists of dielectric substrate coated on both sides with 35 μm thick copper. Holes with a diameter of 1.9 mm are achieved mechanically using a CNC-controlled milling machine entirely through the substrate with a periodicity of a = 2.5 mm along x and y directions. The proposed metamaterial is very simple to manufacture without using traditional lithography techniques, which is a major advantage for a transfer to industrial applications The commercial Isoclad-Arlon printed circuit board, which has a thickness $\boldsymbol{t}$ of 100 μm, a moderate relative permittivity ε_r of about 3.16 and a low loss tangent of about 0.9 % (tan δ ~ 0.009 up to 100 GHz) is used for the design.

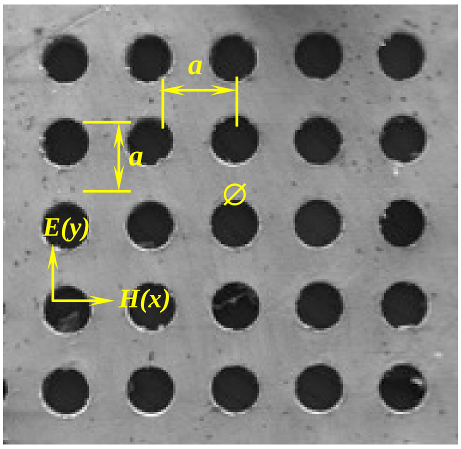


Fig. 1 Photograph of our fabricated prototype with the relevant geometrical dimensions: a = 2.5mm, $\varnothing$ = 1.9mm, the polarization of the electric and magnetic fileds is also illustrated in the figure

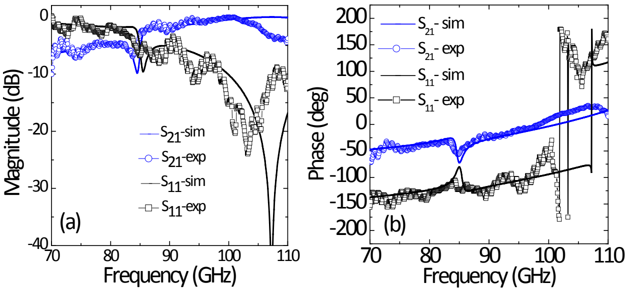


Fig. 2 Magnitudes (a) and phases (b) of the simulated (solid line) and measured (line and symbols) response (transmission and reflexion) to electromagnetic radiation incident on the holes-array fishnet metmaterial

The chosen PCB presents a good mechanical flexibility due to its low thickness, which is a potential good feature for conformity applications like radomes. This metamaterial is excited at normal incidence with electric and magnetic field polarization illustrated in Fig. 2. Note that only one single layer of the metamaterial is taken into account along the direction of propagation k_z.

III. SIMULATIONS AND EXPERIMENTAL VERIFICATIONS

Using HFSS, which is full wave commercial software simulator based on the finite element method, we calculated the magnitudes and phases of the transmission $\boldsymbol{S_{21}}$ and reflexion $\boldsymbol{S_{11}}$coefficients. Experiments have been done by using a non-destructive free-space setup based on a vector network analyser (AB Millimetre$^{\text{TM}}$) with transmitting and receiving horn antennas. The results of our characterization are depicted in Fig. 2. The structure has a pronounced resonance around 85 GHz, we find that the electromagnetic resonance wavelength $\boldsymbol{\lambda}$ is much larger than the size of the unit cell $\boldsymbol{t}$ (thickness of the metamaterial along the direction of propagation $\boldsymbol{z}$) (λ/t=35), the effective medium model could be successfully employed. Although the sizes of the unit cells of the metamaterial along the x and y directions are not much smaller than $\boldsymbol{\lambda}$, diffraction still cannot occur. The reason is that electromagnetic waves are not propagating along the $\boldsymbol{x}$ and $\boldsymbol{y}$ directions [11]. The structure exhibits a good impedance matching ($z'= 1$) at about 107 GHz for the simulation and near 104 GHz for the measurement (see Fig. 2(a)). At these frequencies the reflexion undergoes a phase jump of +180°. The dip in the phase of transmission around 85 GHz indicates the presence of a negative refractive index band (see Fig 2(b)).

IV. EXTRACTION OF EFFECTIVE PARAMETERS

Using the S-parameters retrieval method [12], the complex effective permeabilityμ, permittivityε, wave impedance $\boldsymbol{z}$ and refractive index $\boldsymbol{n}$ have been extracted in Fig 3. The permeability shows a resonant Lorentz dispersion (Fig. 3(a)), while the permittivity is analogous to the Drude dispersion model of the continuous wires (Fig. 3(b)). The negative permeability is the result of a strong resonance response to an external magnetic field while negative permittivity can be achieved by either plasmonic or a resonance response to an external electric field. Around the frequency of resonance, the real part of the effective wave impedance z' is real positive with very low imaginary parts, which attests the passivity of the structure (see Fig. 3(c)). According to what we have mentioned in the previous section, the real part of the effective wave impedance $z'= 1$ near 107 GHz in the simulation and at about 104 GHz in the measurement, which confirms a good impedance matching between the structure and its host medium. Our extracted effective refractive index is negative over a frequency band from 80 GHz to 90 GHz, which includes both Single Negative Metamaterial (SNG:μ'>0 and ε<0) from 80 GHz to 85 GHz and Double Negative Metamaterial (DNG: μ'<0 and ε<0). The negative refractive index is achieved when the condition $P= \mu'\varepsilon''+\mu''\varepsilon'< 0$ is satisfied, as clearly shown in Fig 3(d) and Fig. 3(e), respectively. Several prototypes have been fabricated for different operating frequencies: 35 GHz, 55 GHz, 85 GHz and 94 GHz, which offers a very broad spectral range of functioning, depending on the targeted application. At about 86.3 GHz, the double negative metamaterial (DNM) has a maximum FOM of 3.5 in simulation and about 1.4 in measurement, contrasted to the significantly lower FOM values of the single metamaterial (SNM) as shown in Fig 3(e).

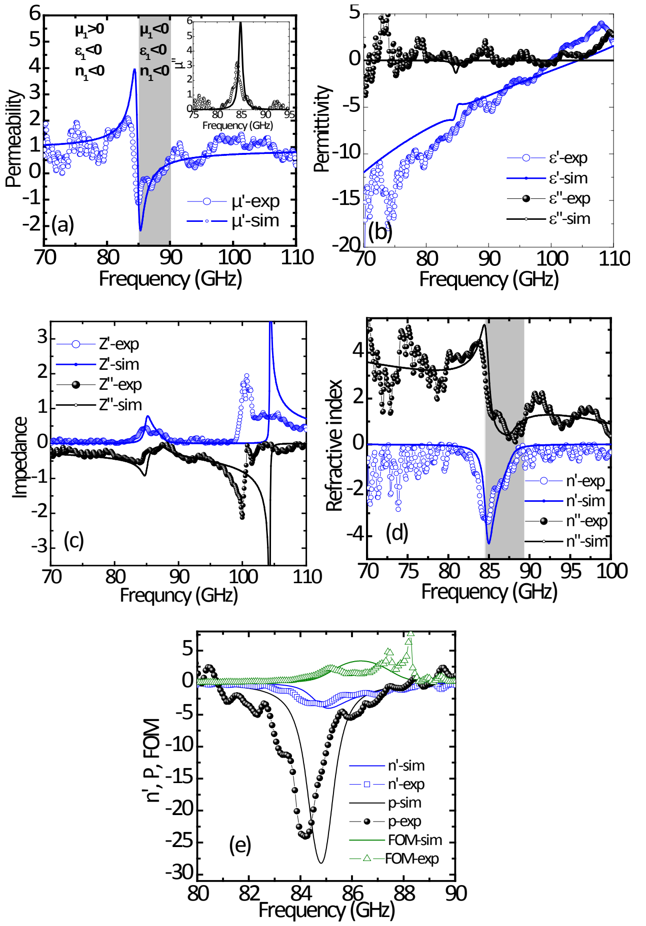
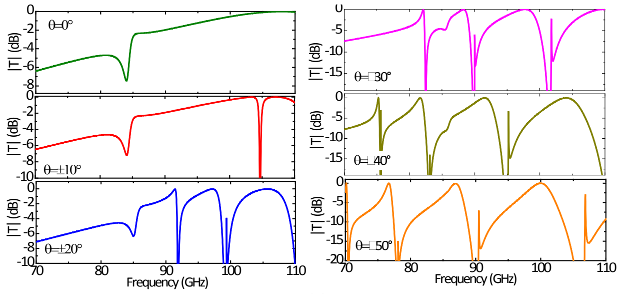


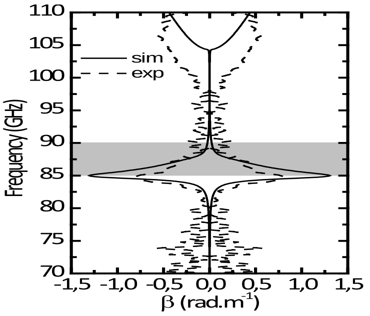
Fig. 3 Extracted electromagnetic properties of a periodic array of our double-sided metal grid fishnet metamaterial unit cell, using the simulated and measured data of Fig. 2. Real and imaginary parts of:permittivity (a), permeability (b), impedance (c) and refractive index (d). Simulated (solid lines) and measured (lines+symbols) curves of real part of the refractive index n′, P=$\mu'\varepsilon''+\mu''\varepsilon'$ and FOM=(-n′/n″) (e). To guide the eye, the spectral regions corresponding to the (DNG) and (SNG) are highlighted by different shadowed areas

V. STABILITY OF THE SPECTRAL RESPONSE FOR DIFFERENT FIELD POLARIZATION ANGLES AND DISPERSION DIAGRAM

The influence of the incident angle $\boldsymbol{\theta_{\text{inc}}}$ on the stability of the response of our investigated holes-array fishnet metamaterial has been studied numerically. The spectral response of our metamaterial is very sensitive to the incident angle $\boldsymbol{\theta_{\text{inc}}}$, as illustrated in Fig. 4(a). Indeed, at ±10°, an additional peak appears around 105 GHz and splits into new peaks, which move gradually toward lower frequencies as the angle of incidence increases.



(a)



(b)

Fig. 4(a) Transmission magnitudes of the investigated holes-array metamaterial for different incident angles (θ_{inc}) from 0° to ±50°, (b) simulated (solid lines) and measured (dashed lines) first-mod dispersion diagram on the contour ΓX of the first Brillouin zone of the holes-array fishnet metamaterial

The resonance at 85 GHz that characterizes the negative refractive zone is not modified up to an incident angle of ±20°. Beyond this angle of incidence, the negative refractive index signature is significantly affected and it completely disappears for an incident angle of about ±50°. In other words, it seems that the structure supports higher order modes that might be very useful for multiple-frequency band applications.

The theoretical and experimental first mode dispersion diagram on the ΓX contour of the first Brillouin zone of our studied metamaterial is depicted in Fig 4(b). The structure exhibits a left-handed propagation, characterized by a negative slope ($d\omega / dk < 0$) within the frequency range 85 GHz - 90 GHz (highlighted regions in Fig. 4(b)) which demonstrates that the phase velocity and group velocity are anti-parallel.

The structure also exhibits a band gap between 90 GHz and 105 GHz approximately in simulation (right horizontal dashed regions in Fig. 4(b)) and between 90 GHz and 98 GHz approximately in measurement (left vertical dashed region in Fig. 4(b)). Beyond the experimental and theoretical frequencies of 98 GHz and 105 GHz respectively, which correspond to the plasma frequencies of the structure, the metamaterial behaves as a right-handed propagation medium of electromagnetic waves.

VI. DEMONSTRATION OF THE NEGATIVE REFRACTION

In order to demonstrate the existence of a frequency band where the refractive index is negative, and to prove a direct consequence of the negative refraction of the electromagnetic wave for the holes-array fishnet metamaterial, a two dimensional metamaterial prism is designed for simulation and measurement. Both simulations and experiments have been performed on the prism characterized by a refractive index that reaches a maximum negative value of about -4 around 85 GHz.

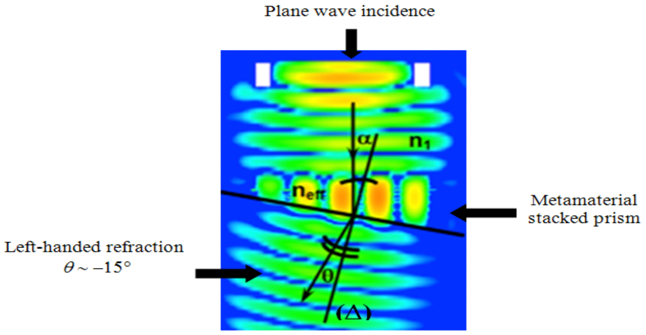


Fig. 5 Stacked-metamaterial-prism-based negative refraction simulation at 85 ghz, n_1 is the refractive index in the air, n_{eff} is the effective refractive index in the prism

We have depicted in Fig. 5 the calculated electric field distribution at the resonant frequency of 85 GHz. The simulation results demonstrate the negative refractive behaviour. Indeed, the refracted beam, which corresponds to the Ez-field, propagates toward a left-handed region with a negative refraction angle of about -15° (in other words, the beam is transmitted in the same side as the incident beam, with respect to the normal axisΔ). One can clearly observe that the magnitude of the Electric field is considerably enhanced within the metamaterial-based stacked prism, which demonstrates the amplification of evanescent modes.

VII. CONCLUSION

In conclusion, we have investigated composite metal-dielectric metamaterial at microwave frequencies exhibiting a negative refractive index. Calculations based on the finite element method have been performed in order to predict the spectral response of our proposed structures. An experimental demonstrator has been fabricated using the mechanical machining approach. Measurements have been carried out using a non-destructive free space setup based on a vector network analyzer and horn antennas so as to validate the numerical predictions. Good agreements have been reported between simulations and experiments. The negative refractive index exhibited by our structure (fishnet metamaterial) has been calculated and measured. And the left handed behaviour has been demonstrated numerically and experimentally.

ACKNOWLEDGMENT

This work has been performed at the University of Bordeaux 1 within the framework of the project “GIS-AMA-SAMM”. The authors would like to thank Eddie Maillard for fabricating the holes-array metamaterials.

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